

Atlantic City DER Recurrent Seminar – May 5, 2004

Continued Airworthiness Assessment Methodologies



AC39-8 (AC39.XX)

Continued Airworthiness
Assessment Methodologies
(CAAM)

Overview
DER Seminar – Atlantic City
5/5/04
Ann Azevedo

Topics

- Introduction - philosophy and benefits
- Background
- How is risk assessed?
- CAAM specifics
- Monte Carlo simulation introduction
- Examples
- Discussion/questions

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CAAM Philosophy

The CAAM philosophy is to respond to threats to continued operational safety with a timeliness and manner in keeping with the severity and probability of the event.

The Benefits of Risk Analysis

- Ensures that continued operation is acceptable
- Allows for objective and consistent assessment of unsafe conditions
- Allows for mitigation of unsafe conditions with the most optimum use of resources within an individual problem
- Helps to prioritize use of resources among multiple problems

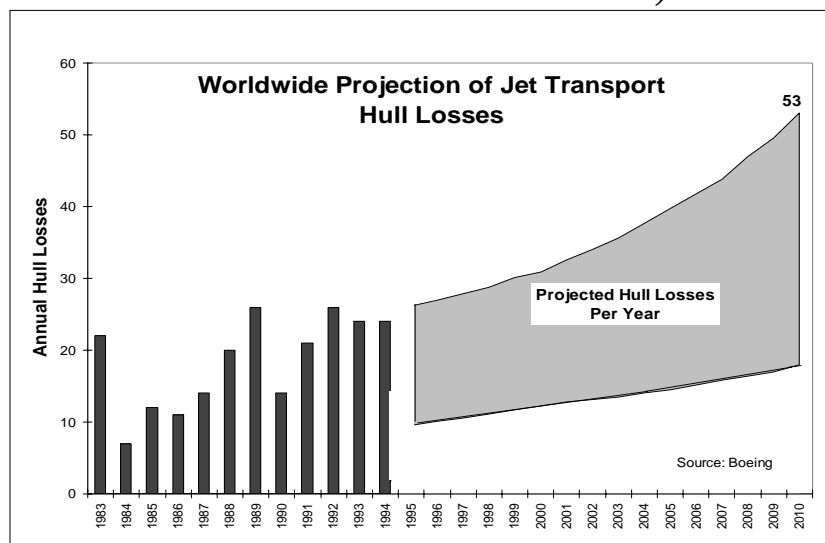
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CAAM Development

- Public perception of aircraft safety is coincident with the number of accidents per calendar time period
- Increase in the number of accidents per calendar time period due to increases in the number of departures
- Available resources must be focused in areas that offer the greatest potential for accident prevention (Pareto principle)

The Status Quo (Time of CAAM Committee Formation)



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AIA CAAM Committee

Formed at the request of the E&PD to develop methods and use historical data to identify and prioritize unsafe conditions based on occurrence probability and consequence

- Occurrence Probability -
 - Tabulate
- Consequence -
 - Standardized aircraft hazard levels
 - Hazard ratio (given a malfunction has occurred, what is the likelihood it is a serious event)

Original draft AC

- Risk assessment process developed and used by E&PD since 1995
- Appendix containing 10 years of engine, propeller and APU events and outcomes summarized and analyzed
 - Data in appendix later issued as Technical Report on Propulsion System and Auxiliary Power Unit (APU) Related Aircraft Safety Hazards (1982-1991 data)
- Desire to have coordinated process with TAD for propulsion

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CAAM AC - Recent Activity

- Revised draft AC coordinated with TAD to expand process to cover propulsion risks
- AC released for public comment - extensive comments received
- Team of US industry, airline and FAA dispositioned comments received
- Revised AC incorporating comment dispositions issued for Public Comment
- AC issued as AC39-8 in September

What is the CAAM Process?

CAAM has two very simple steps:

- Assess the risk
- Compare it to the guidelines

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First, a Few Definitions

- Hazard level. Level of event outcome, as defined by its effect on the aircraft, passengers, and crew.
- Hazard ratio. The conditional probability that a particular powerplant installation failure mode will result in an event of a specific hazard level.

A Note on Hazard Levels

- The CAAM level determination for a particular incident or accident is an objective assessment of what actually happened.
- It does NOT mean that the base event will always result in that outcome!
- It does NOT mean that the base event is defined as a particular CAAM level!

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Hazard Ratios vs. Hazard Levels

- A Hazard Ratio is the conditional probability (percent) of a particular Hazard Level outcome given that a particular base event occurs
- Usually calculated from the outcomes (Hazard Levels) of past events
- This will be discussed in greater depth later

CAAM Hazard Levels

- Level 3 - Serious consequences
 - Substantial damage to aircraft or second unrelated system
 - Uncontrolled fire
 - Rapid depressurization
 - Permanent loss of thrust/power > 1 propulsion system
 - Temporary or permanent inability to climb
 - Temporary or permanent impairment of controllability
 - Smoke/fumes sufficient to cause serious impairment

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CAAM Hazard Levels (cont.)

- Level 4 - Severe consequences
 - Hull loss
 - Serious injuries or fatalities
 - Forced landing

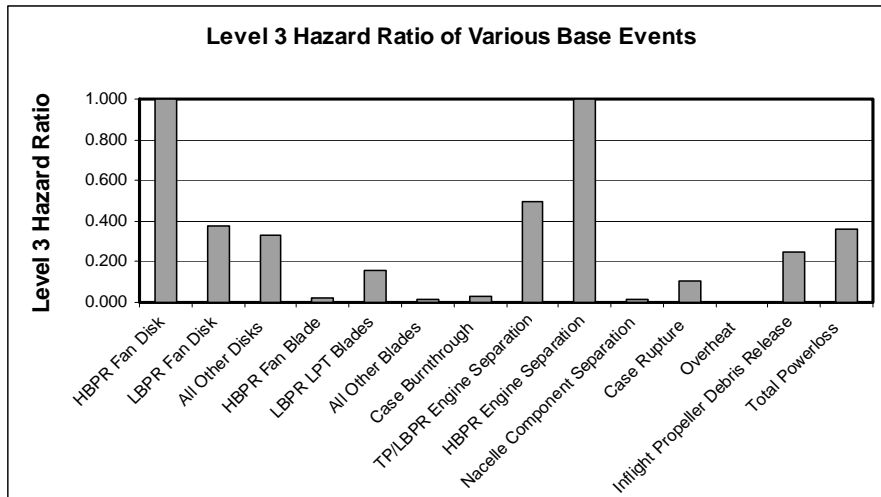
CAAM Hazard Levels (cont.)

- Level 5 – Catastrophic consequences
 - Multiple fatalities, usually with the loss of the airplane

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Hazard Ratios Vary Greatly Depending on the Base Event



More Definitions

Unsafe Condition. A condition which, if not corrected, is reasonably expected to result in one or more serious injuries.

(1) Is reasonably expected. Has a probability of occurrence acceptable to neither the long-term risk guidelines of the AC nor the intent of the applicable product design standards.

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Definitions (cont.)

Risk factor. A quantitative assessment output equal to the average number of future events expected to occur within a given time.

- (1) Uncorrected risk factor - if no corrective actions are incorporated.
- (2) Control program risk factor - during the control program.
- (3) Corrected risk factor - after the final corrective actions.

Assessing Risk

- Components of risk
 - Severity
 - Probability

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Severity

- Basic event is not necessarily the event of interest
- Conditional probability of more severe event (CAAM Hazard Level 3, 4 or 5) given base event – Hazard Ratio

Assessing Risk

- Like any other discipline, risk assessment is a specialized process
- However, like any other discipline, all ASE's should have a basic understanding of techniques

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Assessing Risk – Failure Distributions

Random

- Failures equally likely whatever the age of the component
 - Ex. – fan blade fractures due to birdstrikes
- Many failure modes combined often result in a random distribution (ex. – IFSDs)
- Future risk easy to calculate –
 - Mean Time Between Failure (MTBF) from past data (total hours or cycles divided by number of events)
 - Divide future hours/cycles by MTBF for number of expected future events

Failure Distributions (cont.)

Wearout

- Failures become more likely the older the component gets
 - Ex. – low cycle fatigue
 - Rate of increasing probability of failure can vary
- Most common failure mode for hardware
- Future risk more complicated to calculate – function of current age on each individual part
 - If Weibull distribution, probability of failing within next x hours/cycles (given current age t)
$$= [P(t+x) - P(t)] / [1 - P(t)]$$

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Failure Distributions (cont.)

Infant Mortality

- Failures become less likely the older the component gets
 - Ex. – Maintenance, assembly errors
 - Older parts may become exempt from suspicion
- Often difficult to manage risk
- Future risk function of current age on each individual part

Failure Distributions (cont.)

Other failure distributions are also of interest

- Binomial
 - Ex. – Modeling presence of latent failures
 - Yes/no failure does NOT (necessarily) mean 50-50 probability!
- Poisson
 - Models events
 - The probability of actually having an event given a risk factor (future number of events) is a Poisson function (ex. – a 0.7 risk factor equals a 50% probability of at least 1 event)

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Assessing Risk – CAAM Specifics

The failure distribution describes the population – how is it used to predict future risk?

First – what are the acceptable risk guidelines in CAAM?

CAAM Risk Factor Guidelines

- Control program:
 - ≤ 1.0 level 3+ events (risk factor)
 - $\leq 4.0\text{E-}5$ level 3+ events per flight
 - ≤ 0.1 level 4 events (risk factor)
 - $\leq 4.0\text{E-}6$ level 4 events per flight
- Corrected risk:
 - $\leq 1.0\text{E-}8$ level 3+ events per flight
 - $\leq 1.0\text{E-}9$ level 4 events per flight

No risk factor guidelines for level 5 - learn from the first few years of activity

Data indicate substantial conservatism (actual results vs. predicted results) in E&PD CAAM analyses

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CAAM Risk Analysis Specifics

Estimate the Number of Airplanes Exposed

Determine the number of airplanes for which the unsafe condition may exist or be expected to develop if no corrective action is taken

- Airplanes with engine parts within a certain serial number range, or
- Airplanes with installed engines below a certain total cycles or total hours

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Estimate the Uncorrected Risk Factor

The expected number of events if no action is taken to address the condition

- Estimate the number that are expected to experience the event from the exposed population
- While the event of interest is usually the occurrence of the identified unsafe condition, events of lesser or greater severity may also be analyzed
- Risk factors for CAAM levels 3, 4 and 5 are also calculated to allow for comparison to the risk guidelines
- Risk factors for higher-level events are obtained by multiplying the event risk factor by the applicable hazard ratio

Identify Options for Mitigating Action

- Inspections
- Placards
- Revisions or supplements to the Aircraft Flight Manual (AFM)
- Staggering engines to obtain mixed life engines on a given airplane (for infant-mortality problems)
- Pre-flight checks

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Estimate the Effects of Candidate Actions

- Candidate actions should be evaluated with the appropriate manufacturer, designer, or operators to consider their capacity to reduce the future risk to acceptable levels
- The selected action(s) should consider such issues as confidence in the effectiveness of the corrective action, availability of the resources necessary to support the corrective action, and the ability of the operators to expediently and properly incorporate the corrective action

Estimate Potential Risk Reduction

- Estimate the proposed mitigation program for all actions under consideration, thereby allowing the effects of different programs to be compared
- The objective is to keep the risks to the affected fleet below the applicable guidelines until final action can be incorporated to bring the product back to the level of safety intended by the product's original basis of certification
- If none of the candidate immediate corrective action programs can achieve the needed risk reductions, more aggressive action, including grounding, should be considered

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Estimate Resource Requirements

- Resources are time, material (parts and inspection equipment), labor, shop capacity, parts distribution, operational disruptions and lost revenue
- The extent of these required resources should be estimated to quantify the impact of the AD or other corrective action (such as improved training and interim non-AD actions), allow for timely provisioning, and aid in the determination of desirable tradeoffs between resources and risk
- Data will often be required from the manufacturer(s), operators or both to aid in this process

Rank Practical Candidate Actions

- Given that several candidate actions provide equivalent reduction in risk, they can be readily ranked in desirability regarding the impact on resources
- Small tradeoffs in risk can be accepted where a candidate action with the lower risk is of much greater difficulty to effectively implement or is much more burdensome than a slightly riskier option
- Some highly-effective options may prove not to be in the public interest if the cost to implement them exceeds the potential benefits - care should be taken to not mandate AD actions for which a petition for exemption would likely be granted

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Rank Practical Candidate Actions (cont.)

Each candidate action should be evaluated against the following criteria:

- First and foremost, its effectiveness, meaning its relative reduction of risk
- Availability of resources (shop visit capacity, material availability, personnel, etc.)
- How quickly it can be implemented
- How easy it is to implement
- Its relative cost

Rank Practical Candidate Actions (cont.)

Candidate actions include such items as:

- Manufacturing, maintenance or operational procedural changes
- On-wing or in-shop inspections
- Limitations on time-limited dispatch (TLD)
- Part repairs, replacement, or modifications

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Rank Practical Candidate Actions (cont.)

- The number of cycles or hours between initial and repetitive actions should also be evaluated
- The ideal action would be inexpensive, easy to perform, possible to begin immediately, and 100 percent effective; the real situation often requires trading off these characteristics.
- For example, developing an accurate inspection tool and method that can be used for engines on wing may mean inspection does not begin immediately

Develop and Implement Appropriate Responses

- The objective is to maintain an acceptable level of safety by reducing the risks posed by future events
- Selection of actions, including taking no specific action, should be based on the specific circumstances and an assessment of the risk of future occurrences of the unsafe condition
- Grounding, pending determination of the root cause and appropriate corrective action, is rarely necessary, and should be reserved for situations where the guidelines indicate immediate action is necessary yet no less burdensome effective option is available

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Verify Results of Corrective Actions

- Initial corrective actions, whether immediate reactions or initial considered responses, may not represent the final action required to address the unsafe condition
- Service experience and any other data gathered during the action implementation should be carefully reviewed to increase the validity of the analytical process and the estimated risks

Monitor Implementation and Impacts of the Corrective Actions Taken

- When feasible, the rate of incorporation of the corrective action(s) should be tracked to verify that the action is being implemented in a timely manner
- Inspection results should be analyzed to aid assessment of the extent of the problem
- Service experience should be tracked to ensure that the rate of occurrence is being reduced (not applicable for rare events)
- Service experience and inspection results should be evaluated against predictions of the analysis

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Verify Corrective Actions Were Effective

- Any experience that deviates significantly from expectations or assumptions is grounds to revise the assessment of the situation
- Field experience and inspection results should continue to be monitored to ensure that any interim action (i.e., inspection) continues to validate assumptions and predictions, or to alleviate any consequence of any extra conservatism built into an initial assessment
- Final action (usually part modification or replacement) carries with it an assumption that the causal factors have been effectively eliminated or mitigated with regard to their ability to result in an unsafe condition; field experience should be tracked to validate this assumption
- Check for any unforeseen adverse impacts of corrective actions are identified and evaluated

Follow-on Assessments and Responses

- Initial actions may be insufficient to effectively mitigate the risk to acceptable levels - follow-on responses and actions may be required
- The risk assessment process should be applied to the decisions involved in the use of actions, whether initial or follow-on
- Initial responses may be based upon limited or partial data, and later steps are usually based upon information that is more complete

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CAAM Procedure

- Risk analysis predicts expected number of future events (risk factor) and risk per flight
- Database helps to establish hazard ratio of safety-significant events (CAAM level 3+)
 - use data specific to problem if available
 - industry-wide 1982-1991 data in Technical Report
 - updated data (1992-2000) in AC39-8, Appendix 8
- Control program risk predicted and compared to guidelines

Risk Factor

- Event consequences influence risk factor upper limit
 - Inversely proportional to the severity of the event
- Zero risk is unattainable without immediate intervention (grounding)

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Issues

The Control Program must meet the guidelines for both level 3+ and level 4 risk factor

For events with a high level 4 hazard ratio, the level 4 risk factor will be the controlling number

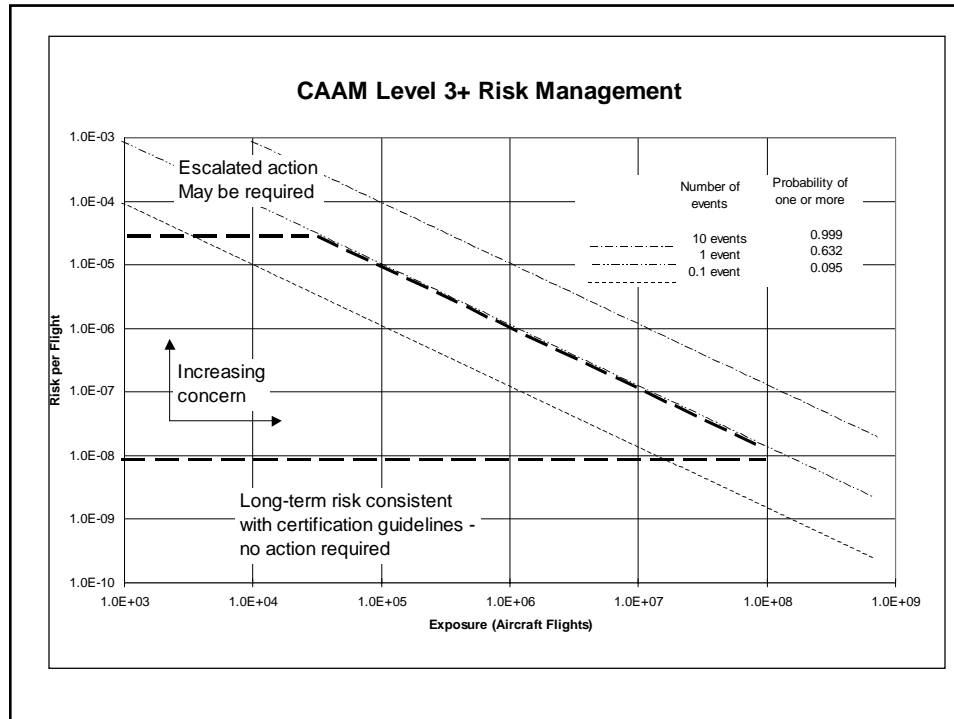
Protection against level 4 events is paramount!

Risk Exposure

- Aircraft flights are calculated until all suspect parts are modified or replaced.
- For uncorrected risk, aircraft flights for a 20-year period are used.

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CAAM Process Summarized

- CAAM and AC 39-8 assist in the management of type-design specific risks
- The safety management process must differentiate the relative importance of safety threats

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CAAM Objectives Summarized

- Risk analysis and CAAM provide a systematic means to
 - identify
 - assess
 - prioritizesafety threats.

Monte Carlo Simulation

The procedure most often used by the OEMs for calculating risk for the Engine and Propeller Directorate is a numeric method based on computer simulations which quantify the expected number of future events (risk factor) for specific problems as a function of specific operational and maintenance constraints.

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Simulation Goals

- Optimizes inspection and modification programs
 - Achieves risk factor goal
 - Minimizes operational impact
 - Predicts provisioning requirements

Simulation Model

- Statistically based
 - Weibull analysis
 - Monte Carlo techniques
- Represents sum of knowledge about problem
 - Realistic assessment of known conditions
 - Conservative assessment of unknowns
 - Engineering judgment

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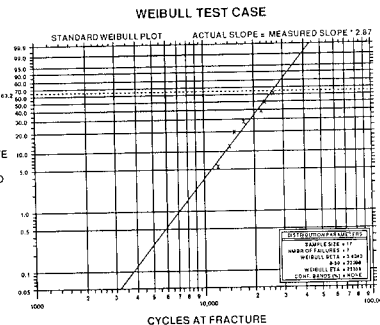
WEIBULL ANALYSIS

Used to determine probability of an event (fracture, removal, etc.) vs. part age based on available experience.

Data Set

Cycles at Fracture	Cycles on 'Good' Parts (Suspensions)
12000	3000
15000	4000
16000	5000
18000	11000
22000	17000
23000	19000
26000	20000
	25000
	27000
	29000

CUMULATIVE
PERCENT
OCCURRED



Monte Carlo

Monte Carlo is a simulation technique that assigns random numbers to the outcomes of a statistical distribution. The probability of a given value is determined by the random numbers assigned to that value.

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Simulation Procedure

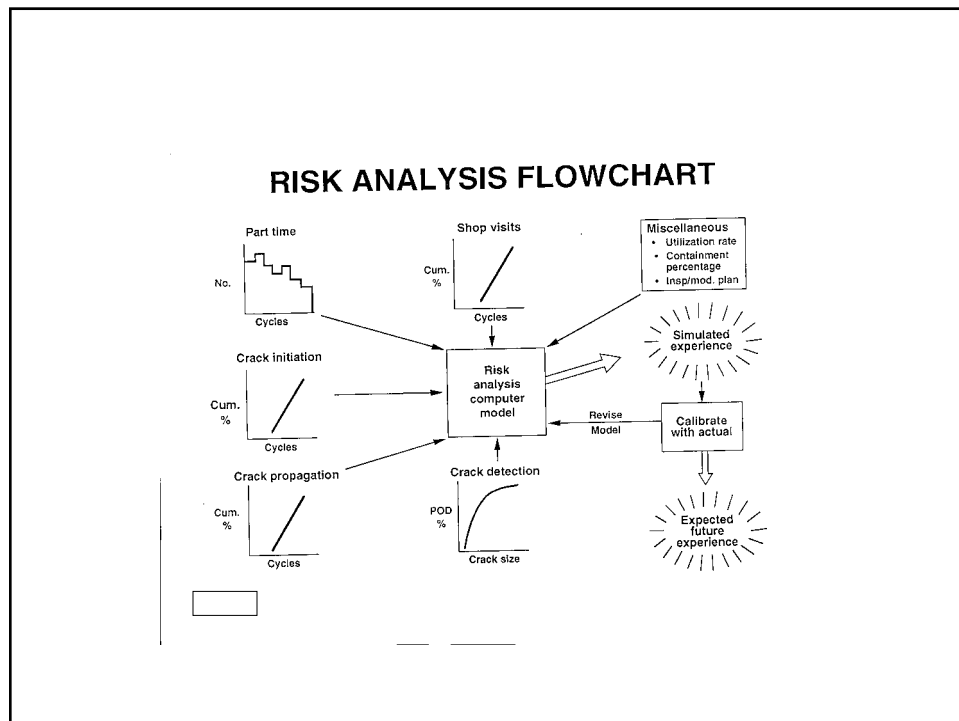
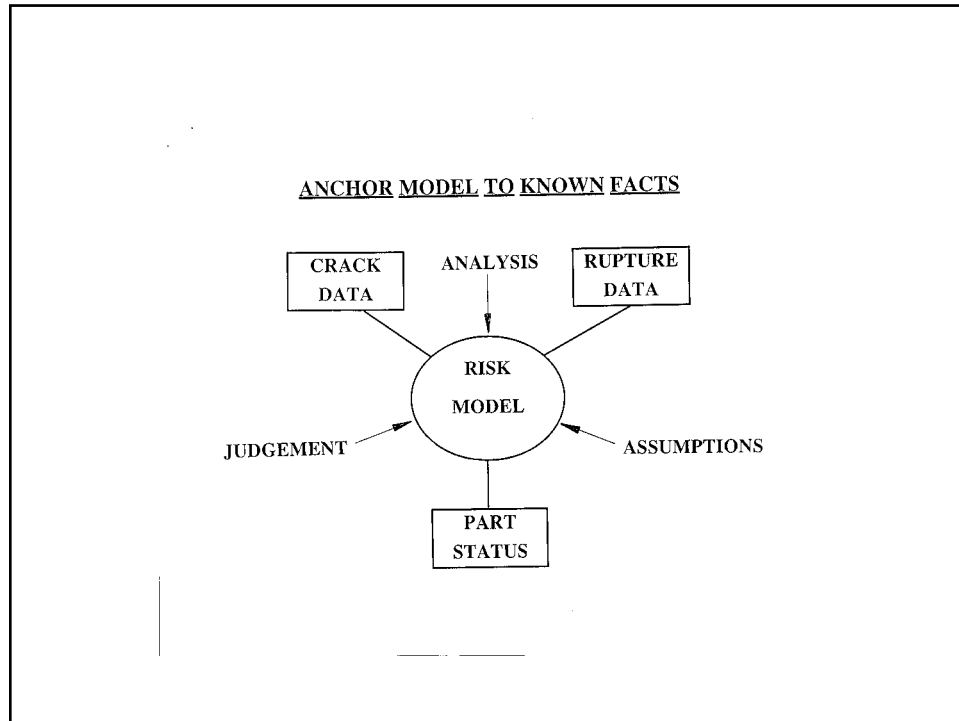
- Define event of interest
- Establish upper limit for risk factor (CAAM guidelines)
- Define simulation model characteristics
- Define relevant distributions
 - Part life
 - Shop visits
- Define operational and maintenance constraints

Simulation Procedure (cont.)

- Create computer model
- Define inspection/modification scenarios
- Calibrate model
 - Should predict experience to date
- Output information:
 - Risk factor
 - Sensitivity analyses
 - Parts requirements

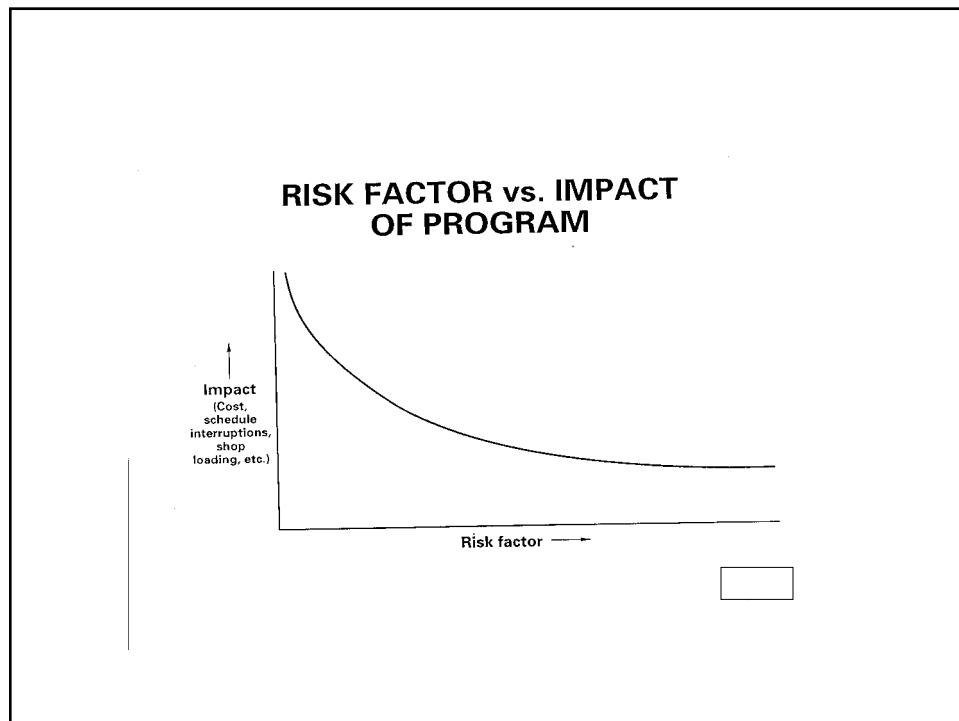
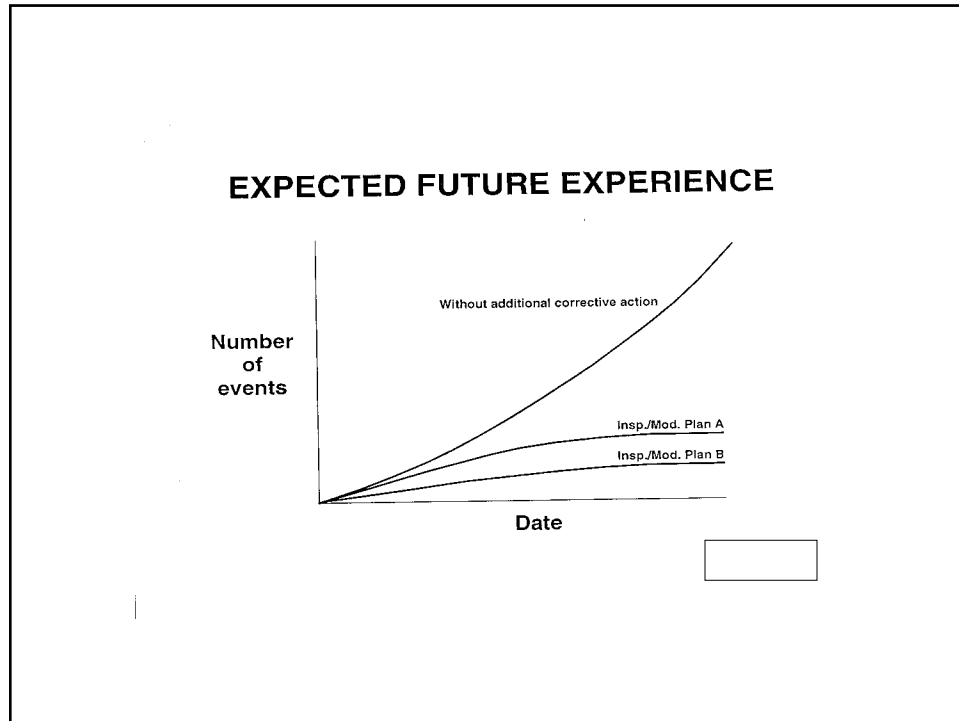
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Summary - Monte Carlo Simulation

- Maintaining flight safety while minimizing economic impact requires the use of risk analysis in the decision-making process
- Monte Carlo simulation enables comparison of various interventions on risk factor and economic impact

CAAM Example

Compressor Disk Fracture

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Example

- 8HPC disk (low-bypass engine) fractures during takeoff roll.
- The fracture occurs prior to V1, and the takeoff is safely aborted.
- The fractured disk has 12,508 cycles part life.

Example (cont.)

- The fracture is uncontained, but does not cause any damage to the aircraft, or injury to any passenger or crew.
- Failure investigation reveals the disk fractured in low-cycle fatigue due to corrosion. The investigation further indicates the corrosion occurred because the failed part had not been properly coated during manufacture.

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Example (cont.)

- 433 disks (including spares) of the suspect part number are currently in service, and are considered to be at risk of a repeat event.
- 1.3 additional disk fractures are predicted assuming all current parts are allowed to remain in service until their certified retirement life (15,000 cycles).

Example (cont.)

- While this event did not result in serious injury or other CAAM level 4 event, data on similar disk fractures over the past 15 years indicate a 7 CAAM level 3 and 4 events out of a total of 10 uncontainments
- 4 of those events (40 percent) resulted in hull loss or fatality (CAAM level 4) due to on-ground fire

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Example (cont.)

- Coordination with the aircraft manufacturer indicates that, for this installation (wing-mounted engine), 50 percent of the uncontainments would be at least CAAM level 3, and 80 percent of the level 3s would be hull loss/injury events (level 4)
- The assumption is made that 40 percent of the events ($0.50 \times 0.80 = 0.40$) would be expected to result in serious injury or other CAAM level 4 event

Example (cont.)

- 1.3 events predicted events
- $1.3 \times 0.40 = 0.52$ Level 4 events if no action is taken
- Average per-flight CAAM level 4 risk
 - $0.52 / (433 \text{ disks} \times 5000 \text{ cycles (avg. life remaining)})/\text{disk} /$
 $2 \text{ cycles/flight} = 4.8 \times 10^{-7}$
 - Below the guideline for immediate action (4.6×10^{-6} per-flight for CAAM level 4 events, so the disks are allowed to remain in service while an inspection and replacement plan is developed.

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Example (cont.)

- Over the next few weeks, while a plan is being developed, a number of retired disks are located and inspected, along with several disks in engines currently undergoing scheduled shop visit
- One disk is found to have a crack resulting from a corrosion pit. These inspection findings, along with structural modeling by the engine manufacturer, allow for a more refined quantitative analysis
- The Monte Carlo simulation is revised, and is performed against a number of inspection and replacement scenarios to find one that acceptably mitigates the risk of level 4 events

Example (cont.)

- OEM submits a plan to the E&PD which calls for
 - replacement of the disks at next shop visit
 - engines above 10,000 cycles part life to be removed no later than within the next 2,000 cycles
- The simulation predicts that this plan would result in 0.18 uncontainments
 - 0.09 would be at least level 3 ($0.50 \text{ level } 3 \times 0.18$)
 - 0.07 would be level 4 ($0.40 \text{ level } 4 \times 0.18$)
 - Both the level 3 and level 4 predictions are below the CAAM risk guidelines

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Example (cont.)

- E&PD reviews the assumptions and results of the risk analysis. Though the E&PD would like to further reduce the risk of this event, it agrees that a more aggressive schedule would result in significant service disruptions
- Disks are inspected as they are replaced, with the results compared at regular intervals to the month-by-month predicted crack findings from the Monte Carlo simulation

Example (cont.)

- Subsequent inspection findings indicate the initial risk analysis is somewhat conservative. However, both the engine manufacturer and the E&PD feel that no alleviation of the disk replacement schedule should be pursued due to the potential seriousness of another event
- After 4-½ years, the last of the suspect disks is replaced. No additional events have occurred during that period

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